Potassium-Argon Dating of Glacial Erratics

by David Beery

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In cooperation with
Dr. R. Fleck , and
Dr. G. Faure

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R. J. Fleck

INTRODUCTION

The ice flow patterns of Pliestocene continental glaciations in North America are quite complicated. To try to determine some information on these flow directions, an attempt was made to trace some glacial erratics to their source area by radiometric dating. At the northern edge of Georgian Bay, in Canada, north of Lake Huron, a border of two of the Canadian Shield radiometric age provinces is located (Figure 1). K-Ar ages of rocks of these provinces differ by as much as 1.5 billion years. Since the rocks of each age range do not occur beyond the age boundary, glacial erratics derived from each should be easily identified and give a good indication of ice movement.

Samples were collected at Arcanum, in western Ohio, Muncie, in eastern Indiana, and Marion, in north central Indiana. The Muncie sample was too badly altered for age determination, so biotite from the two remaining samples was dated by the K-Ar method.

GEOLOGIC HISTORY

Canadian Shield

Nearly half of Canada is occupied by the Canadian Shield, a region of Precambrian rocks that form the bedrock of central Canada. A land area of 1,864,000 square miles is represented, and the Canadian Shield extends south into the United States in the Lake Superior and Adirondack regions. The Canadian Shield is surrounded by Phanerozoic sedimentary rocks that, due to the stable influence of the Precambrian basement, are little disturbed (Stockwell, 1970, p. 44).

The Canadian Shield is divided into seven structural provinces on the basis of internal structure and radiometric ages (Fig. 1). Boundaries are drawn along major unconformities or orogenic fronts. The younger provinces truncate the older, with all provinces being defined on structural trends, style of folding, and radiometric ages (Stockwell, 1970, p. 44). The provinces of concern in this paper are the Grenville and Superior Provinces, as the Southern Province is too far west of the Ohio-Indiana border to be considered as a boulder source.

On the basis of K-Ar ages and a few Rb-Sr whole rock ages, four major orogenies have been detected (Stockwell, 1970, p. 49). The oldest is the Kenoran, at 2480 million years, and the youngest is the Grenville at 955 m. y. (mean values). The two intermediate orogenies, the Hudsonian (1735 m. y.) and Elsonian (1370 m. y.), are not involved in this study.

The Grenville Province cuts the Superior Province on a line trending northeast from Georgian Bay, although there is evidence the Superior Province may have originally extended

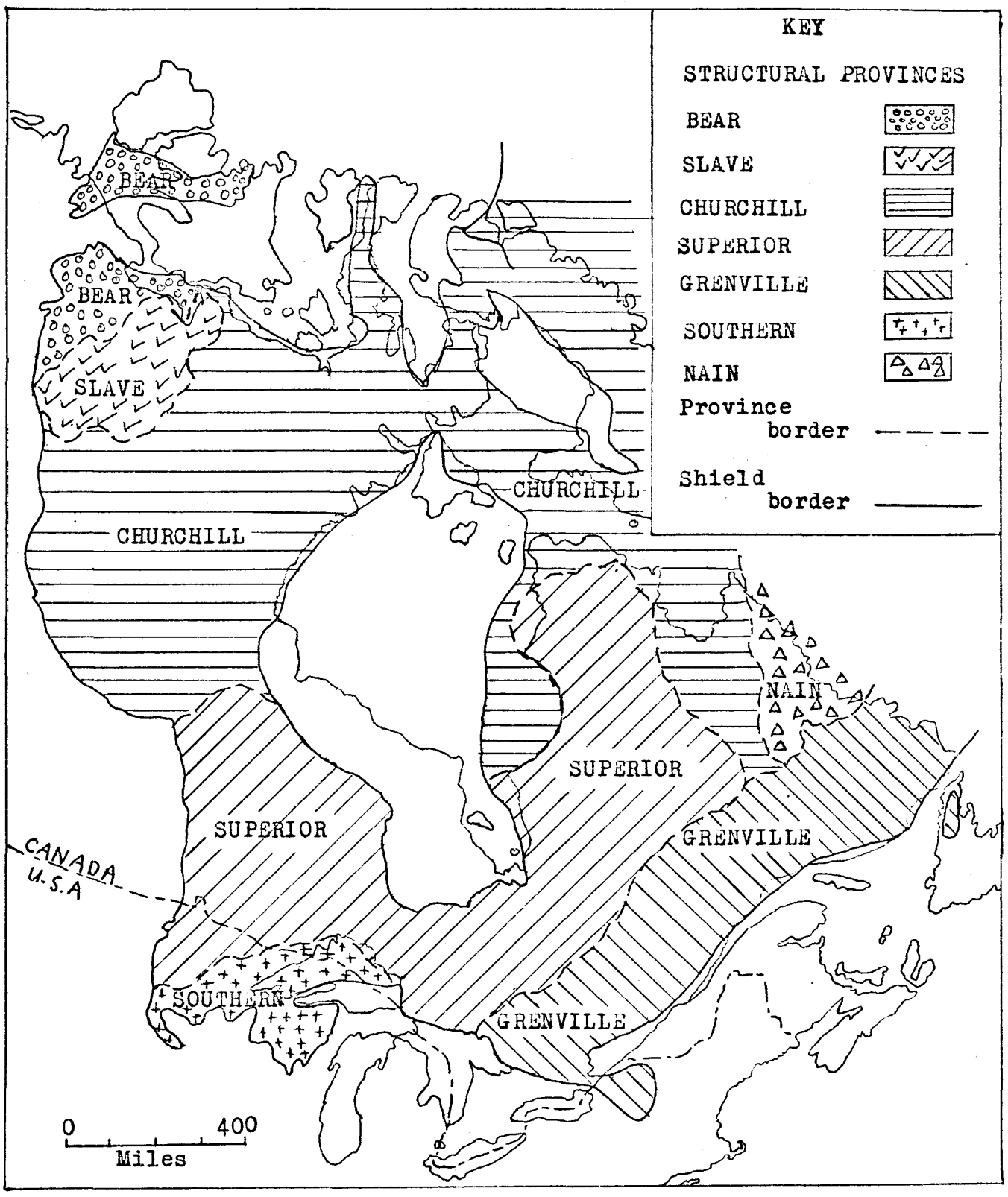

Figure 1. Canadian Shield and Provinces (Geology and Economic Minerals of Canada, 1970).

into the Grenville Province (Emslie, 1970, p. 121). Medium to high-grade regional metamorphism is evident in the Grenville Province. Average K-Ar ages of 2,480 m. y.(McGlynn, 1970, p. 54) indicate the Superior Province was deformed during the Kenoran orogenic period. Average ages for the Grenville Province suggest a 955 m. y. mean for the Grenville orogeny. Ages determined from glacial erratics south of these provinces should show the origin of the boulders.

Glaciation

The glacial history of this area shows five major ice advances, and their related interglacial intervals. The advances are, in order, the Nebraskan, Kansan, Illinoian, Early Wisconsin, and Late Wisconsin. Drift sheets left by the retreating ice indicate the extent of the advances, and these are traced until covered by a later drift. Soils and other weathering products of the interglacial periods are also buried.

From the structure of the drift sheets, a "layering" type of structure is observed (Baker, 1920). In many places, however, the older drift sheets were completely destroyed by the younger, and are not present. The first ice advance, the Nebraskan, was not as extensive as the later advances, and consequently is buried beneath the later drifts in most places. Later drift sheets are exposed and can be studied directly.

Three centers of ice accumulation fed the advances (Cornwall, 1970). The first three advances arose from two western

centers, the Keewatin, just west of Hudson Bay, and the Cordilleran in the Rockies (Fig. 2). From the Labrador center on the Labrador plains, ice flowed outward to feed the Early and Late Wisconsin ice sheets.

Topographic effects caused by the ice are varied (Baker, 1970). Thousands of small lakes were formed, and the Great Lake basins were scooped out. Pre-glacial drainage patterns were reversed or rerouted. Recessional moraine left by the retreating ice created a very uneven surface. Currently, the "elastic rebound" due to the release of the weight of three to eight miles of ice is resulting in a gentle upwarping of the previously depressed region.

Samples

Sample B-Ar-1 was collected two miles east of Arcanum, Ohio, from a private farm. Boulders of all sizes were present, but no gravel was seen. The area is cultivated, and piles of rocks could be seen in corners and along the edges of fields. B-Ma-3 was collected north of Marion, Indiana, 1½ miles into eastern Wabash county along state route 218. This area is mostly farmland and generally flat. As at Arcanum, boulders of all sizes and types were observed.

The erratics collected represent the last glaciation in this area, the Late Wisconsin. So, any flow directions determined will be Wisconsin flow.

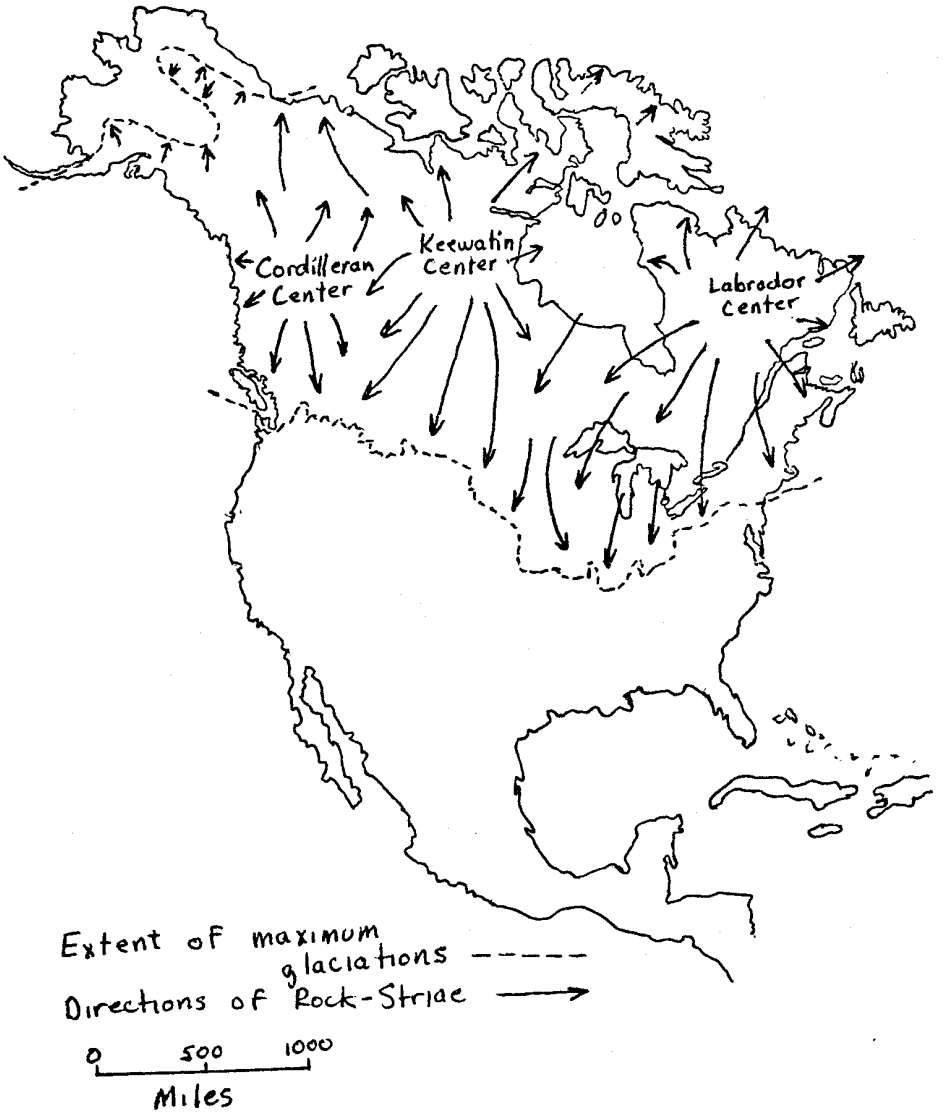

Figure 2. Ice accumulation centers and flow directions (Cornwall, 1970).

AGE EQUATION

Radioactive decay is a process where the number of atoms that decay per unit time, $-dN/dt$, is proportional to the number of atoms present, N. So

$$-\frac{dN}{dt}=\lambda N, \tag{1-1}$$

where λ is the decay constant and represents the probability that an atom will decay in unit time.

Integrating between $N=N_o$ at $t=0$ and $N=N$ at $t=t$,

$$\int_{N_o}^{N}\frac{dN}{N}=-\int_{0}^{t}\lambda dt\ , \tag{1-2}$$

$$\log_e \frac{N}{N_o}=-\lambda t\ , \tag{1-3}$$

$$N=N_o e^{-\lambda t} \tag{1-4}$$

which is the basic radioactive decay equation, N_o=initial number of atoms present, N=number of atoms at time t.

The number of atoms lost of N_o will equal the gain of D, the daughter product:

$$N_o-N=D \tag{1-5}$$

$$N_o=N+D \tag{1-6}$$

Substituting (1-6) into (1-4), we get

$$D=N(e^{\lambda t}-1)\ . \tag{1-7}$$

Solving for t, to calculate ages, gives

$$t=\frac{1}{\lambda}\log_e\left(\frac{D}{N}+1\right)\ , \tag{1-8}$$

which is the general age equation.

For branching decay with two daughter products, as in potassium, equation (1-7) becomes

$$D_1+D_2=N\left[e^{(\lambda_1+\lambda_2)t}-1\right]\ . \tag{1-9}$$

For the specific decay of K^{40}, equation (1-9) becomes

$$Ar^{40}_{rad} + Ca^{40}_{rad} = K^{40}\left[e^{(\lambda_\epsilon+\lambda_\beta)t} - 1\right] , \qquad (1\text{-}10)$$

where λ_ϵ and λ_β are the decay constants for the two branches, K^{40} to Ar^{40} and K^{40} to Ca^{40}. The Ar^{40}_{rad} and Ca^{40}_{rad} represent only the radiogenic daughter products.

The decay constants for Ar^{40} and Ca^{40} from K^{40} are

$$\lambda_\epsilon = 0.585 \times 10^{-10}/\text{yr.}$$
$$\lambda_\beta = 4.72 \times 10^{-10}/\text{yr.}$$

The combined decay constant is

$$\lambda = \lambda_\epsilon + \lambda_\beta = 5.305 \times 10^{-10}/\text{yr.}$$

For calculating dates based on the decay of K^{40} to Ar^{40} alone, equation (1-10) becomes

$$Ar^{40}_{rad} = K^{40}\frac{\lambda_\epsilon}{\lambda_\epsilon+\lambda_\beta}\left[e^{(\lambda_\epsilon+\lambda_\beta)t} - 1\right] \qquad (1\text{-}11)$$

where Ar^{40}_{rad} and K^{40} are the number of atoms of these elements present today per unit weight of rock.

Solving equation (1-11) for t gives

$$t = \frac{1}{\lambda_\epsilon+\lambda_\beta}\log_e\left[\frac{Ar^{40}_{rad}}{K^{40}}\left(\frac{\lambda_\epsilon+\lambda_\beta}{\lambda_\epsilon}\right) + 1\right] . \qquad (1\text{-}12)$$

This is the potassium-argon age equation.

Substituting in the decay constant values, equation (1-12) becomes

$$t = 1.885 \times 10^9 \log_e\left[9.068\frac{Ar^{40}_{rad}}{K^{40}} + 1\right] , \qquad (1\text{-}13)$$

where Ar^{40} and K^{40} are determined and used in the equation. For young rocks, a simplification can be used, but for ages older than Cenozoic, equation (1-13) is used.

Five assumptions are made when using equation (1-13) to

determine geologic dates.

1. The decay of K^{40} (its half-life) is constant, regardless of chemical or physical conditions.

2. The present-day proportion of K^{40} to K_{total} is the same for all materials dated by the K-Ar method.

3. All argon in the rock is radiogenic or atmospheric; the atmospheric argon is detected and corrected for.

4. The rock has been a closed system since time zero, when the rock cooled. K^{40} and Ar^{40} have not been lost or gained, as can happen during a later heating of the rock.

5. Compared to its age, the time or duration of cooling of an igneous rock or mineral is short. This is necessary to establish the time-zero concept.

ANALYSIS

Preparation

The boulder to be analyzed is crushed, ground, and sieved. Only the particles trapped between the 42 and 60 mesh screens are used. This material is washed with water through another screen to remove dust and small particles, then dried. The crushed, cleaned rock is then suspended in bromoform. Minerals with a specific gravity greater than bromoform (2.88) sink and are collected. Magnetics are removed with a magnet and the remaining biotite is paper shaken, the flat biotite grains sticking to the paper. Finally, the biotite is hand picked through a binocular microscope to remove combined grains and other contaminating minerals.

Argon Measurement

The pure biotite is weighed, placed in a molybdenum crucible, put in a sample bottle, and attached to the extraction line. After baking out the system overnight, the biotite is fused by a high-frequency induction heating coil, thus releasing the trapped argon. During fusion, a spike of tracer argon, its volume and isotope composition being known, is admitted to the first half of the line. The gases in the line are collected in a charcoal finger immersed in liquid nitrogen after a copper oxide furnace has oxidized hydrocarbons and hydrogen gas, and a dessicant has removed water vapor.

The high vacuum valve is then opened, the gases are drawn into the second half of the line by another charcoal finger immersed in liquid nitrogen, and the valve is closed. The liquid nitrogen is removed from the finger, and the gases are

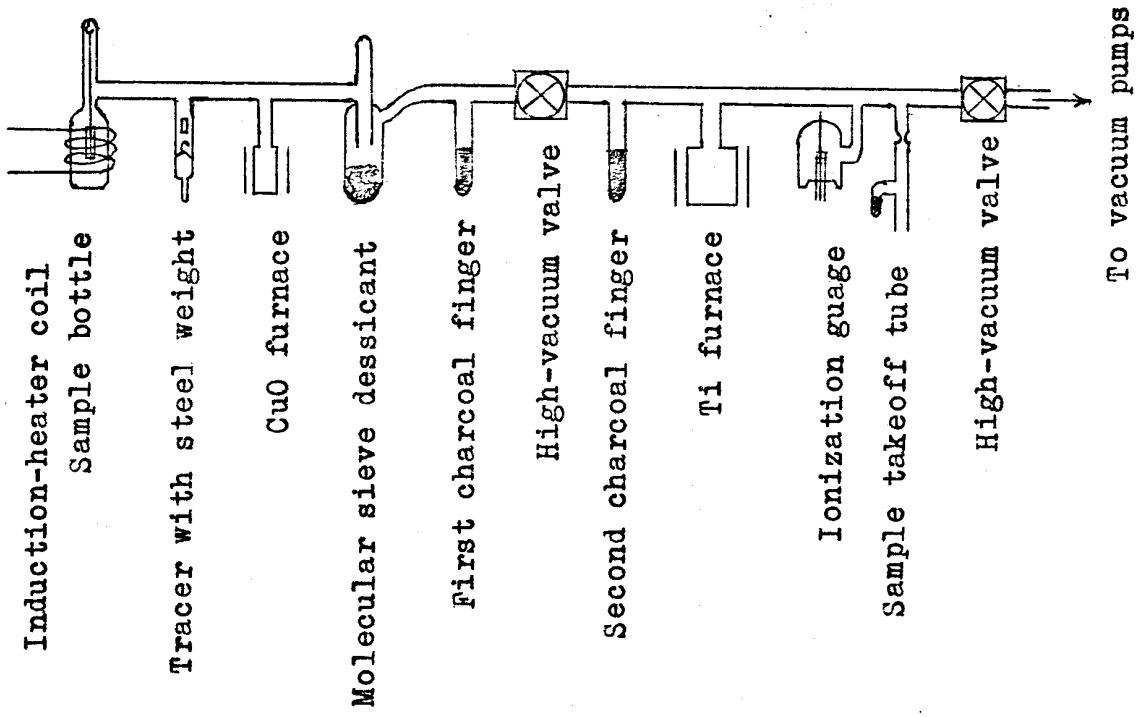

Figure 3. Argon Extraction Line (Dalrymple and Lanphere, 1969).

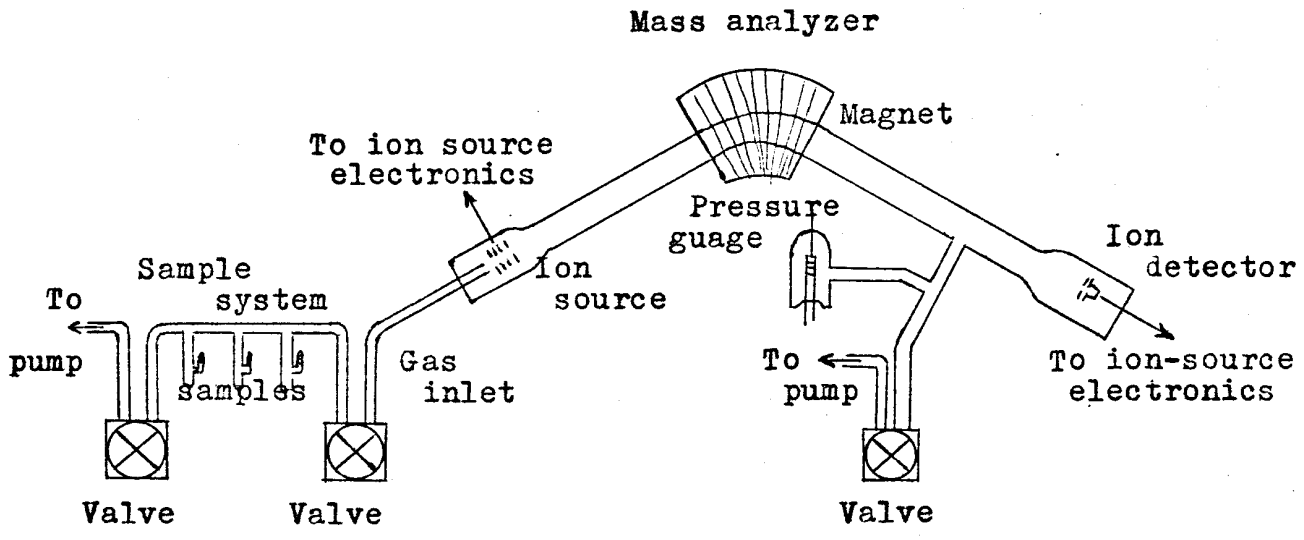

Figure 4. Mass Spectrometer (Dalrymple and Lanphere, 1969).

released to a titanium metal furnace. The reactive gases (O_2, N_2) combine with the titanium metal, and are removed from the line. The remaining gas, which is almost pure argon but including other noble gases as well, is collected in the sample take-off tube using another charcoal finger and liquid nitrogen. The take-off tube is removed, and the gas analyzed on a mass spectrometer.

The mass spectrometer is an instrument that analyzes elements according to the masses of their isotopes. Argon is admitted to the spectrometer where it is ionized, accelerated, and deflected by a magnet. The amount of deflection depends on the charge-to-mass (e/M) value; in this case, Ar^{36}, Ar^{38}, and Ar^{40} are deflected into different paths. This deflection is measured on an ion detector that prints out the data as a series of peaks on a strip chart. These peak heights are measured and Ar^{40}/Ar^{38} Ar^{38}/Ar^{36} ratios are calculated. Since the composition of argon changes with time, the ratios must be plotted versus time and extrapolated back to time zero (when the gas sample was first admitted to the spectrometer). These extrapolated values are used in the age equation.

Potassium Measurement

A small amount of biotite is dissolved in sulfuric and hydrofluoric acids and heated overnight to drive off silicon tetrafluoride (gas) and excess acids. More unwanted elements are precipitated as insoluble carbonates or sulfates, and carefully filtered out. The remaining solution contains potassium, sodium, and minor magnesium. The potassium concentration of

this solution is measured on a Zeiss PF-5 flame photometer.

The flame photometer uses the principle that when the potassium in the solution is introduced to the flame, the potassium atoms will become excited and emit characteristic radiations. This radiation is reflected from a mirror through a condensing lens, K-filter, and photomultiplier tube to a detector. This detector measures the intensity of the light emission on a bar scale. The unknown potassium solution is measured between two standard solutions of known concentrations of lithium. Using the data from the scale, the potassium concentration of the solution is determined, and with the weight of the biotite originally dissolved, the percent K_2O in the mineral is calculated.

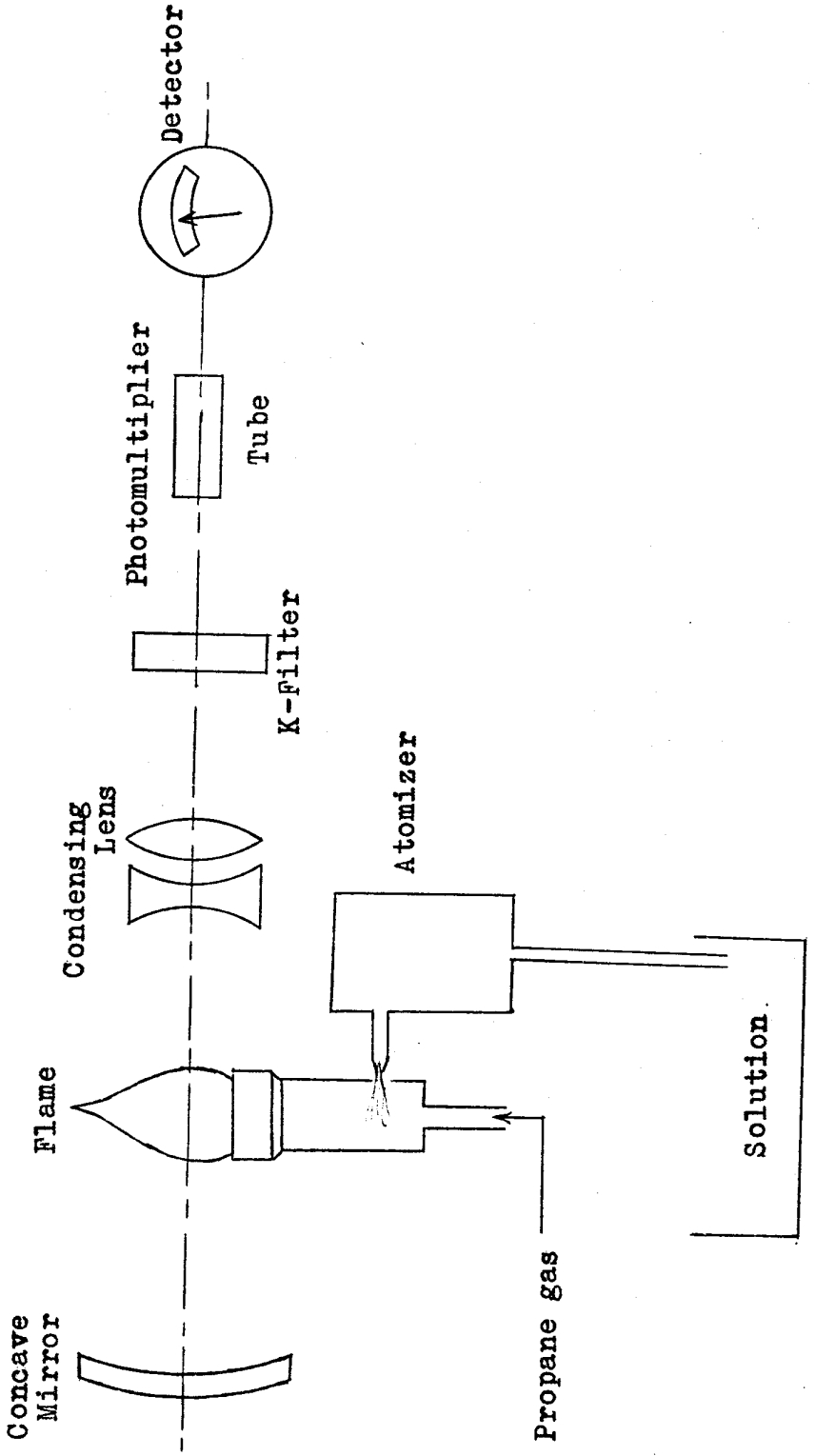

Figure 5. Schematic diagram of a Zeiss PF-5 flame photometer.

RESULTS

Sample	% K^+	Moles Ar^{40}/gm.	% Ar^{40}_{rad}	Ar^{40}/K^{40}
B-Ar-1	7.711 %	1.7479×10^{-8}	94.3 %	7.4482×10^{-2}
B-Ma-3	8.000 %	1.6548×10^{-8}	97.3 %	6.7967×10^{-2}

Sample	Calculated Age	Std. Deviation	% Std. Deviation
B-Ar-1	972.8×10^6 yr.	12×10^6 yrs.	1.19 %
B-Ma-3	905.1×10^6 yr.	11×10^6 yrs.	1.21 %

Discussion of Results

These dates should be examined for possible inaccuracies. If at some time after its formation the rock should become re-heated, argon could be lost. However, no major deformations since the Grenville orogeny in the Canadian Shield have been detected. Extraneous argon trapped at the time of formation will result in incorrect dates, but extraneous argon is uncommon in biotite. Weathering contaminations are nullified by careful preparation and removal of altered or impure biotite grains by hand. Therefore, overall reliability of these dates is good, and they should be accurate.

Sample B-Ar-1 was dated at 972 million years, and B-Ma-3 was dated at 905 million years. The first sample is what was hoped for, but B-Ma-3 is in obvious disagreement with the 2,500 million year Superior Province erratic hypothesized. Since both sample dates lie within its range of radiometric potassium-argon dates, they are almost definitely Grenville

in origin.

Since sample B-Ma-3 was collected almost due southwest of the north edge of Georgian Bay (the most western point of the Grenville Province), the ice had to have flowed in a more westerly direction than this. Fortunately, this is in agreement with Leverett and Taylor (1915) for Late Wisconsin glaciation in this area. Advancing from the direction of the Lake Erie basin was the Erie lobe, which almost certainly derived its boulders from the Grenville Province.

CONCLUSIONS

I believe both samples that were dated were collected from the outermost edge of the Erie ice lobe. To find boulders of Superior Province origin, one need only to go further west or north, where deposits of the Lake Michigan and Saginaw lobes would be encountered. If it had not been for the extreme westerly flow of the Erie lobe, I believe my original guess of the Ohio-Indiana border for a separation of Superior and Grenville rocks would be a good one.

This is only a small study, and cannot adequately define the distribution of erratics of a given age. To obtain a representative picture, a large number of erratics must be dated and plotted. From this, an areal distribution of Superior and Grenville boulders could be found. I suspect a sharp boundary would be improbable, and that a gradational one is to be expected.

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